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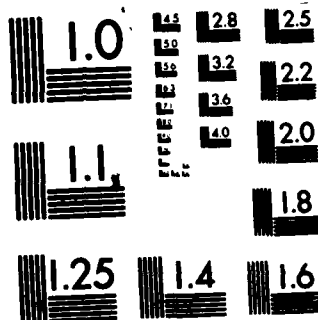
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CONTENTS

I.	INTRODUCTION.....	1
II.	THEORY.....	3
III.	ANALYSIS.....	7
IV.	DISCUSSION.....	10
V.	CONCLUSIONS.....	11
	ACKNOWLEDGMENTS.....	11
	REFERENCES.....	15



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VELOCITY SHEAR STABILIZATION OF THE CURRENT CONVECTIVE INSTABILITY

I. INTRODUCTION

Large scale structure in plasma density enhancements in the auroral F layer ionosphere has been a topic of continued research over the past several years (Vickrey et al., 1980; Keskinen and Ossakow, 1982; 1983a,b; Tsunoda and Vickrey, 1983). Theoretically these so called F region plasma "blobs" have been shown to be susceptible to the $\underline{E} \times \underline{B}$ gradient drift instability (EBI) (Linson and Workman, 1970) and in an $\underline{E} \times \underline{B}$ stable geometry to the current convective instability (CCI) (Ossakow and Chaturvedi, 1979), or a combination of the two (Vickrey et al., 1980; Keskinen and Ossakow, 1982). The current convective instability was originally discussed in the context of the positive column of a laboratory gas discharge by Lehnert (1958), and Kadomtsev and Nedospasov, (1960). Ossakow and Chaturvedi (1979) suggested that the diffuse auroral precipitation, constituting a weak magnetic field aligned current (\hat{z}), could destabilize an inhomogeneous plasma having the density gradient pointing in the direction perpendicular (northward, \hat{x}) to the magnetic field. The unstable waves have wavevectors pointing in the direction perpendicular (eastward, \hat{y}) to both the ambient geomagnetic field and the density gradient. DNA Wideband satellite observations (Rino et al., 1978) indicated that a regularly occurring scintillation enhancement due to F region ionospheric irregularities can be identified in the nighttime auroral zone data. This data is characterized by diffuse auroral particle precipitation and total electron content (TEC) gradient pointing northward. Furthermore, the dominant modes appear to be in the north-south direction parallel to the density gradient in contrast to the predictions of the linear theory. Indeed, Chaturvedi and Ossakow (1979) have shown that waves parallel to the density gradient are generated by a nonlinear mode coupling mechanism.

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There is increasing evidence that a strong velocity shear exists in the diffuse auroral region (Kelley et al., 1976; Fejer et al., 1983; S. Basu, private communication, 1983). The east-west plasma velocity is sheared as one moves in the north-south direction. The coupling to the neutral atmosphere, where the neutral flow velocity usually is strongly sheared, probably generates this plasma velocity shear. Recent calculations have shown that velocity shear has a strong stabilizing influence on interchange instabilities, such as the Rayleigh-Taylor instability (Hamieri, 1979; Guzdar et al., 1982; 1983) and the $\underline{E} \times \underline{B}$ instability (Perkins and Doles, 1975; Huba et al., 1983) leading one to anticipate similar effects in the case of the CCI also.

In this paper we investigate the effects of velocity shear on the CCI and its role in producing large scale east-west structure in ionospheric F layer plasma blobs (Tsunoda and Vickrey, 1983). We find that velocity shear stabilizes the short wavelength modes ($k_y L > 1$, where k_y is the east-west mode number, L is the density gradient scale length) and thus excites a long wavelength mode.

The organization of this paper is as follows. In the next section we present the general nonlocal theory and present its results in the third section. We discuss the results and apply them to the diffuse auroral ionosphere in the fourth section, and the fifth section contains the conclusions.

II. THEORY

The geometry we use is as follows. The background magnetic field and the field aligned currents are along the z-direction ($\underline{B} = B \hat{z}$; $\underline{V}_d = V_{dz} \hat{z}$). The density gradient and the inhomogeneous electric field [$E_{ox}(x)$] are along the x-direction (northward). The inhomogeneous electric field gives rise to an $\underline{E} \times \underline{B}$ sheared flow along the negative y direction (eastward).

The basic assumptions used in the analysis are as follows: (i) the perturbed quantities vary as $\delta f \sim \delta f(x) \exp[i(k_y y + k_z z - \omega t)]$, where k_y and k_z are the wavenumbers along the y and z directions and $\omega = \omega_r + i\gamma$, implying growth for $\gamma > 0$; (ii) the ordering in the frequencies is such that $\omega, \nu_{in}(\nu_{ei}) \ll \Omega_i(\Omega_e)$, where ν_{in} and ν_{ei} are the ion-neutral and electron-ion collision frequencies and Ω_e and Ω_i are the electron and ion cyclotron frequencies, respectively; (iii) we retain the ion inertia effects, thereby including the ion polarization drift, but ignore the electron inertia; and (iv) we ignore finite-Larmor radius effects by limiting the wavelength domain to $k\rho_i \ll 1$, where ρ_i is the mean ion Larmor radius.

A key feature of our analysis is that a nonlocal theory is developed. That is, the mode structure of the potential in the x direction, the direction in which the density and flow velocity are assumed to vary, is determined by a differential equation rather than an algebraic equation obtained by Fourier analysis. This technique allows one to study modes which have wavelengths comparable to the scale sizes of the inhomogeneities (i.e., $k_y L < 1$, where L represents the scale lengths of the boundary layer). In fact, nonlocal theory is essential to describe the Kelvin-Helmholtz instability driven by a transverse velocity shear (Mikhailovskii, 1974).

Based on the assumptions described above, the fundamental fluid equations used in the analysis are continuity and momentum transfer in the neutral frame of reference

$$0 = -e(\underline{E} + (1/c)\underline{V}_e \times \underline{B}) - m\nu_{ei}\underline{V}_e \quad (1)$$

$$M \frac{d\mathbf{V}_i}{dt} = e(\mathbf{E} + (1/c)\mathbf{V}_i \times \mathbf{B}) - Mv_{in} \mathbf{V}_i \quad (2)$$

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{V}_j) = 0 \quad (3)$$

where $m(M)$ is the electron (ion) mass, subscript j denotes species (e for electrons and i for ions), \mathbf{V} is velocity and \mathbf{E} is electric field, n is density, c is speed of light, and e is the absolute value of the electron charge. From eqs. (1) and (2) we obtain the zeroth order perpendicular electron and ion velocities as

$$\mathbf{V}_{e\perp} = + (c/B) \mathbf{E} \times \hat{\mathbf{z}} + O(v_{ei}/\Omega_e), \quad (4)$$

$$\mathbf{V}_{i\perp} = + (c/B) [\mathbf{E}_\perp \times \hat{\mathbf{z}} + (v_{in}/\Omega_i) \mathbf{E}_\perp + (1/\Omega_i) (\mathbf{V}_0 \cdot \nabla) \mathbf{E}_\perp], \quad (5)$$

where $\Omega_i = eB/Mc$ is the ion cyclotron frequency.

Taking the dot product of eqs. (1) and (2) with $\hat{\mathbf{z}}$, we obtain the zeroth order parallel velocities as

$$V_{ez} = -e E_{oz} / mv_{ei}, \quad (6)$$

$$V_{iz} = e E_{oz} / Mv_{in}. \quad (7)$$

We perturb equations (1)-(3) and linearize them in the electrostatic limit. We substitute $\mathbf{E} = -\nabla\phi = -\nabla(\phi_0(x) + \delta\phi)$, $\mathbf{V}_\alpha = \mathbf{V}_\alpha + \delta\mathbf{V}_\alpha$, and $n = n_0(x) + \delta n$ into eqs. (1)-(3). Since the equilibrium quantities vary in the x direction we do not Fourier analyze in the x direction. We Fourier analyze in the y and z directions. Using eqs. (4) and (5) along with eqs. (1) and (2) we obtain the perturbed velocities in the perpendicular direction as

$$\delta \underline{V}_{e1} = +(c/B) \delta \underline{E}_1 \times \underline{\hat{z}} + O(v_{e1}/\Omega_e), \quad (8)$$

$$\delta V_{ix} = \frac{(c/B)}{(1 + V_{oy}'/\Omega_i)} \left[-ik_y \delta \phi + \frac{(i\omega - ik_y V_{oy}' - v_{in})}{\Omega_i} \frac{\partial}{\partial x} \delta \phi \right], \quad (9)$$

$$\delta V_{iy} = (c/B) \left[\frac{\partial}{\partial x} \delta \phi - \frac{(\omega - k_y V_{oy}' + iv_{in})}{\Omega_i} k_y \delta \phi \right]$$

where $V_{oy}' = -(c/B) E_{ox}$. From eqs. (1,2) and (6,7) the perturbed parallel velocities are given as

$$\delta V_{ez} = -e \delta E_z / m v_{e1}, \quad (10)$$

$$\delta V_{iz} = e \delta E_z / M v_{in}. \quad (11)$$

We substitute eqs. (4) thru (11) in eq. (3) and assume quasi-neutrality, $\delta n_e = \delta n_i = \delta n$, to obtain the mode structure equation for the perturbed electrostatic potential as (where we have dropped δ from $\delta \phi$ and indicate the perturbed potential by ϕ)

$$\phi'' + p\phi' + q\phi = 0 \quad (12)$$

where

$$p = \epsilon + (iv_{in}/\omega_2) \bar{k}^2 v_{oy}'/\omega_1 \quad (13)$$

$$\begin{aligned} q = & -k_y^2 - i k_z^2 (\Omega_e/v_{e1}) (\Omega_i/\omega_2) - \bar{k}^2 (k_z v_{oz}'/\omega_1) (\Omega_i/\omega_2) \\ & + k_y (V_{oy}' + v_{oy}' \epsilon)/\omega_2 \\ & + (iv_{in}/\omega_2) \left\{ \left[\bar{k}^2 v_{oy}' \omega/\omega_1^2 - (k_y v_{oy}') \right] [(n_o'/n_o)/\omega_1 \right. \\ & \left. + ik_z^2 (\epsilon v_{oy}'/\omega_1) (\Omega_e/v_{e1}) \right\}, \end{aligned} \quad (14)$$

where we assumed $V'_{oy}/\Omega_i \ll 1$ and ignored terms of $O(v_{ei}/\Omega_e)$ and

$$V_{oz} = (V_{ez} - V_{iz}), \quad \epsilon = n'_o/n_o,$$

$$\bar{k}^2 = ik_z^2 (\Omega_e/v_{ei}) - k_y \epsilon \quad (15)$$

$$\omega_1 = \omega - k_y V_{oy} - k_z V_{oz}, \quad \text{and} \quad \omega_2 = \omega + i\nu_{in}.$$

The primes indicate derivatives with respect to x . Equation (12) is similar to the equations that have been derived in the context of the Rayleigh-Taylor (Guzdar et al., 1982; 1983) and $\underline{E} \times \underline{B}$ instabilities (Huba et al., 1983). In the absence of the velocity shear ($V'_{oy} = V''_{oy} = 0$) the first three terms in $q(x)$ (eq. 14) yield the nonlocal current convective instability. Equation (12) is solved numerically in various parameter domains and the results are presented in the next section.

III. ANALYSIS

Before solving eq. (12) we consider some known limiting cases. First, in the absence of field aligned currents ($V_{oz} = 0$), for a homogeneous ($\nabla n = 0$) collisionless ($v_{in} = 0$) plasma eq. (12) yields the well known transverse ($k_z = 0$) Kelvin-Helmholtz instability (Mikhailovskii, 1974)

$$\phi'' + \left(-k_y^2 + \frac{k_y V_{oy}''}{(\omega - k_y V_{oy})} \right) \phi = 0 \quad (16)$$

The Kelvin-Helmholtz instability is shown in Fig. (1) curve A (Michalke, 1964). The velocity profile used is $V_{oy} = \bar{V}_{oy} \tanh(x/L)$. We see from the figure that the collisionless Kelvin-Helmholtz mode is unstable in the domain $0 < k_y L < 1$ with the growth rate maximizing at $k_y L \sim 1.5$ with a maximum value of $0.18 \bar{V}_{oy}/L$.

In the absence of the velocity shear we obtain

$$\phi'' + \epsilon \phi' + \left[-k_y^2 + ik_z^2 \frac{\Omega_e}{v_{ei}} \frac{\Omega_i}{\omega} + \frac{k_z V_{oz}}{\omega} \frac{\Omega_i}{\omega + iv_{in}} \left(ik_z^2 \frac{\Omega_e}{v_e} - k_y \epsilon \right) \right] \phi = 0 \quad (17)$$

Equation (17) describes the nonlocal current convective instability. In the local limit, $\partial/\partial x \ll k_y$, we obtain the local dispersion equation (Chaturvedi and Ossakow, 1981)

$$\omega^2 + \omega [iv_{in} + i(k_z^2/k_y^2)(\Omega_e \Omega_i / v_{ei})] - (k_z/k_y) \Omega_i V_{oz} \epsilon = 0. \quad (18)$$

The solution of eq. (18) yields the growth rate (Chaturvedi and Ossakow, 1981) with $\omega = \omega_r + i\gamma$ as

$$\gamma = \frac{(k_z/k_y) (v_{ei}/\Omega_e) V_{oz} \epsilon}{(k_z^2/k_y^2) + (v_{ei} \Omega_i / v_{in} \Omega_e)} \quad (19)$$

for $\bar{v}_{in}^2 > 4 (k_z/k_y) V_{oz} \epsilon \Omega_i$, where $\bar{v}_{in} = v_{in} + (k_z^2/k_y^2) (\Omega_e \Omega_i / v_{ei})$. Note that for instability k_z/k_y , v_{ei} , V_{oz} , and ϵ have to be nonzero. In fact, the optimum value of k_z/k_y can be calculated by maximizing eq. (19) with respect to k_z/k_y .

The growth rate maximizes at

$$k_z = k_y (v_{ei} v_{in} / \Omega_e \Omega_i)^{1/2}, \quad (20)$$

with a maximum value

$$\gamma_{\max} = \frac{1}{2} V_{oz} \varepsilon (v_{ei} \Omega_i / v_{in} \Omega_e)^{1/2}. \quad (21)$$

For $v_{ei} / \Omega_e = 10^{-4}$, $v_{in} / \Omega_i = 10^{-4}$,

$$(\gamma / V_{oz} \varepsilon)_{\max} \sim 0.5 \quad (22)$$

Now we solve eq. (17) numerically for various k_y using the density profile

$$n_o(x) = \bar{n}_o (1 + \delta \tanh(x/L)) / (1 - \delta) \quad (23)$$

shown in figure 2 for $\delta = 0.8$.

Figure (1) curve B shows the growth rate normalized to V_{oz}/L as a function of $k_y L$ for $\delta = 0.8$ and k_z given by eq. (20). We note that the growth rate increases monotonically with $k_y L$ and asymptotes to the local growth rate (eq. 22).

We now introduce the velocity shear and solve eq. (12) numerically. We use the density profile given in eq. (23). The velocity profile is determined self-consistently from the zeroth order continuity equation

$$\nabla \cdot (n_o \underline{V}_o) = 0. \quad (24)$$

The eigenvalues are determined for various values of the parameter $\hat{s} (\equiv \bar{V}_{oy} / V_{oz})$, which serves as a measure of the velocity shear. In Fig. (3) we plot the growth rates normalized to the shear-free current convective growth rate, $\gamma / (V_{oz}/L)$, as a function of the normalized wavenumbers, $k_y L$. We choose $v_{ei} / \Omega_e = 10^{-4}$, $v_{in} / \Omega_i = 10^{-4}$, and $\delta = 0.8$. Curve A gives the case $\hat{s} = 0$ (same as curve B, Fig. (1)). Curves B, C and D are for $\hat{s} = 0.5, 1$, and 2 , respectively. We can draw several conclusions from this figure. First, velocity shear stabilizes the short wavelength modes

(Perkins and Doles, 1975; Guzdar et al., 1982; 1983; Huba et al., 1983). Second, the growth rate maximizes at $k_y L \sim 1.5$ for $\hat{s} = 0.5$; and as \hat{s} is increased the peak growth rate decreases and the growth rate maximizes at longer wavelengths. For $\hat{s} = 2$, the growth rate maximizes at $k_y L \sim 0.55$ with $\gamma_{\max} \sim 0.083(V_{oz}/L)$. Third, when $\hat{s} = 1$, i.e., when the horizontal flow velocity is of the order of the vertical plasma drift velocity, modes with $\lambda \sim (2\pi/0.9)L$ are the fastest growing modes ($\gamma_{\max} \sim 0.142 V_{oz}/L \sim 0.142 V_{oy}/L$). We note that as $\hat{s} \rightarrow \infty$ the V'_0 and V''_0 terms dominate in eq. (14) and the growth rate curve peaks around $k_y L \sim 0.45$ (not shown in the figure) resembling curve A of fig. 1.

IV. DISCUSSION

Recent experiments conducted at Chatanika (Tsunoda and Vickrey, 1983) indicate that high latitude F-region plasma blobs have an east-west plasma density structure with scale sizes of 150 km and greater. Even though these experiments did not measure the velocity shear in this region, other evidence (Kelley and Carlson, 1977) indicates the presence of a strong east-west flow velocity shear of the order $1 - 20 \text{ sec}^{-1}$ in the diffuse auroral region. Assuming that the east-west flow is $\sim 250 \text{ m/s}$ and the shear scale length (of the order of the density gradient scale length; $L_N = L_V$) is 25 km, Fig. (3) shows that the generalized current convective instability has perpendicular scale sizes of order 150 km ($\hat{s} = 1$; $V_{oy} = V_{oz}$; $k_y L = 0.9$). The corresponding growth rate is given as $\gamma \sim 0.142 (V_{oz}/L) \sim 0.142 \cdot 10^{-2} \text{ s}^{-1}$ (around 10 minutes e-folding time). For larger shears, for example, with the east-west flow velocity, V_{oy} , twice that of the field aligned flow, V_{oz} , the instability generates irregularities of scale sizes around 300 km, but with a smaller growth rate, $0.08 (V_{oz}/L)$ (20 min e-folding time scale for V_{oz}/L around 10^{-2} s^{-1}).

Since velocity shear has similar effects on the $\underline{E} \times \underline{B}$ gradient drift instability (Perkins and Doles, 1975; Huba et al., 1983) it is important to compare our present results with the results of Huba et al. (1983). Referring to Fig. (5) of the paper by Huba et al., we see that east-west flow comparable to the equilibrium north-south flow (due to the horizontal electric fields generating the $\underline{E} \times \underline{B}$ instability) excites modes with wavelengths $\sim 60 \text{ km}$ ($k_y L = 2.6$, $L = 25 \text{ km}$). The growth rate of these modes is $\sim 0.5 (V_{ox}/L)$ with e-folding times of the order 3 minutes (for $V_{ox}/L \cdot 10^{-2}$). From this we can see that in the diffuse auroral region, the generalized CCI and EBI (CCI and EBI with velocity shear) can excite long wavelength modes with east-west scale sizes of 100 km or greater. However, we point out that in the absence of the $\underline{E} \times \underline{B}$ instability (zero westward electric field in the presense of say a poleward density gradient on a blob) the soft particle precipitation causing in turn currents of moderate strength $\sim 250 \text{ m/s}$ ($4 \mu\text{A/m}^2$, $n = 10^{11} \text{ m}^{-3}$) can still excite the long wavelength modes.

V. CONCLUSIONS

We have studied the effects of velocity shear on the current convective instability. We have shown that velocity shear suppresses the short wavelength modes and preferentially excites a long wavelength mode with $k_y L < 1$. This suggests that a generalized current convective instability (CCI with east-west flow velocity shear) with currents $\sim 4 \mu\text{A}/\text{m}^2$ (~ 250 m/s parallel flow) can possibly excite modes with wavelengths of 150 km or more. Since the $\underline{E} \times \underline{B}$ instability can also excite long wavelength modes ($\lambda \sim 60$ km with a westward electric field $\sim 10 \text{mV/m}$, and north-south flow \sim east-west flow), we conjecture that the soft particle precipitation alone can destabilize a stable $\underline{E} \times \underline{B}$ diffuse auroral F region geometry by the CCI (Ossakow and Chaturvedi, 1979). In turn, The CCI in the presence of velocity shear can generate irregularities in the long wavelength domain.

We note that a unified treatment of current convective and $\underline{E} \times \underline{B}$ instabilities, with velocity shear and magnetic shear and nonlinear effects included, is needed in order to come to a better understanding of the morphology of the irregularities evident in auroral F region plasma enhancements. This subject is presently under investigation and will be presented in a future paper.

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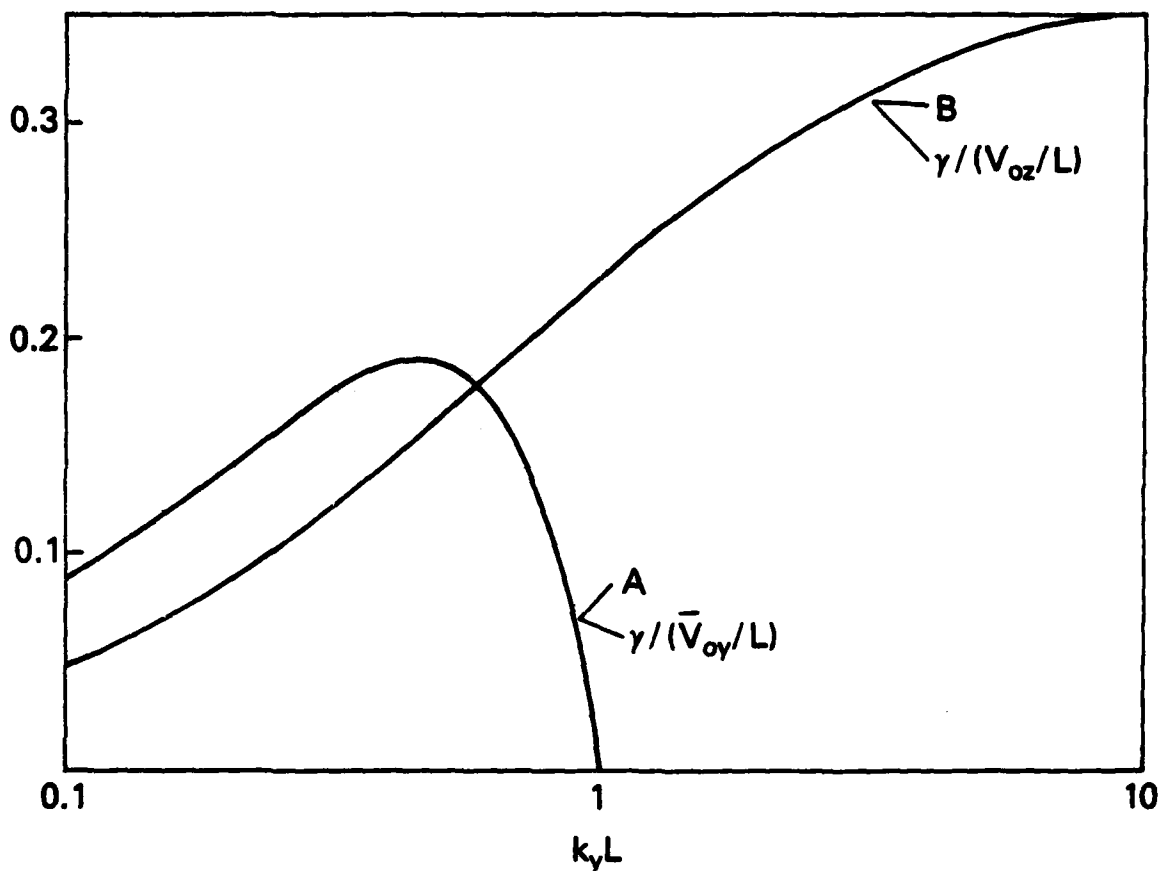


Figure 1. Normalized growth rate versus $k_y L$ curves for Kelvin-Helmholtz (curve A) and current convective (curve B) instabilities. Curve A refers to velocity profile $V_{oy} = \bar{V}_{oy} \tanh x/L$. Curve B refers to the density profile of eq. (23), with $\delta = 0.8$, and $v_{in}/\Omega_i = 10^{-4}$, $v_{ei}/\Omega_e = 10^{-4}$.

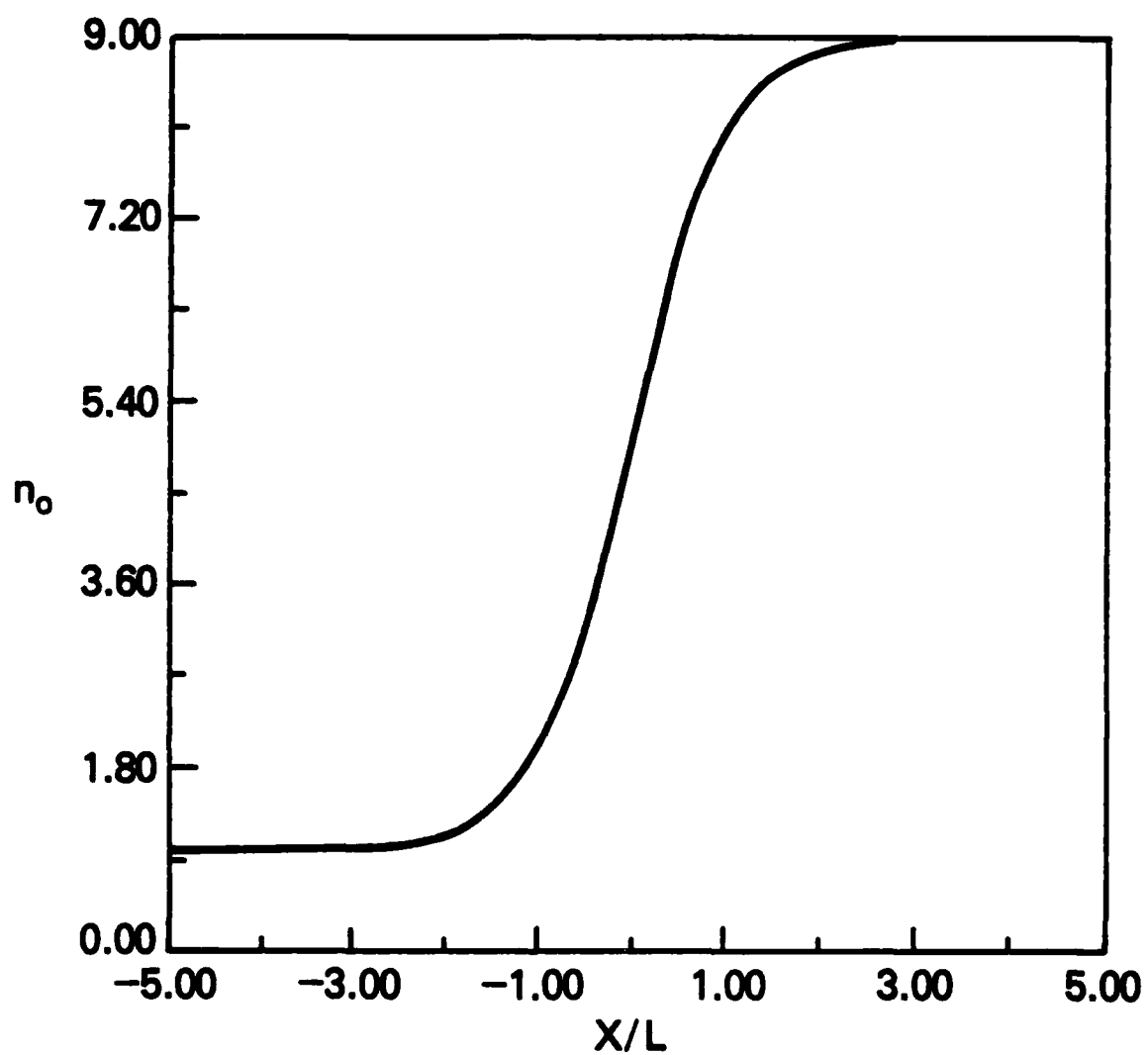


Figure 2. Density profile given in eq. (23) for $\delta = 0.8$.

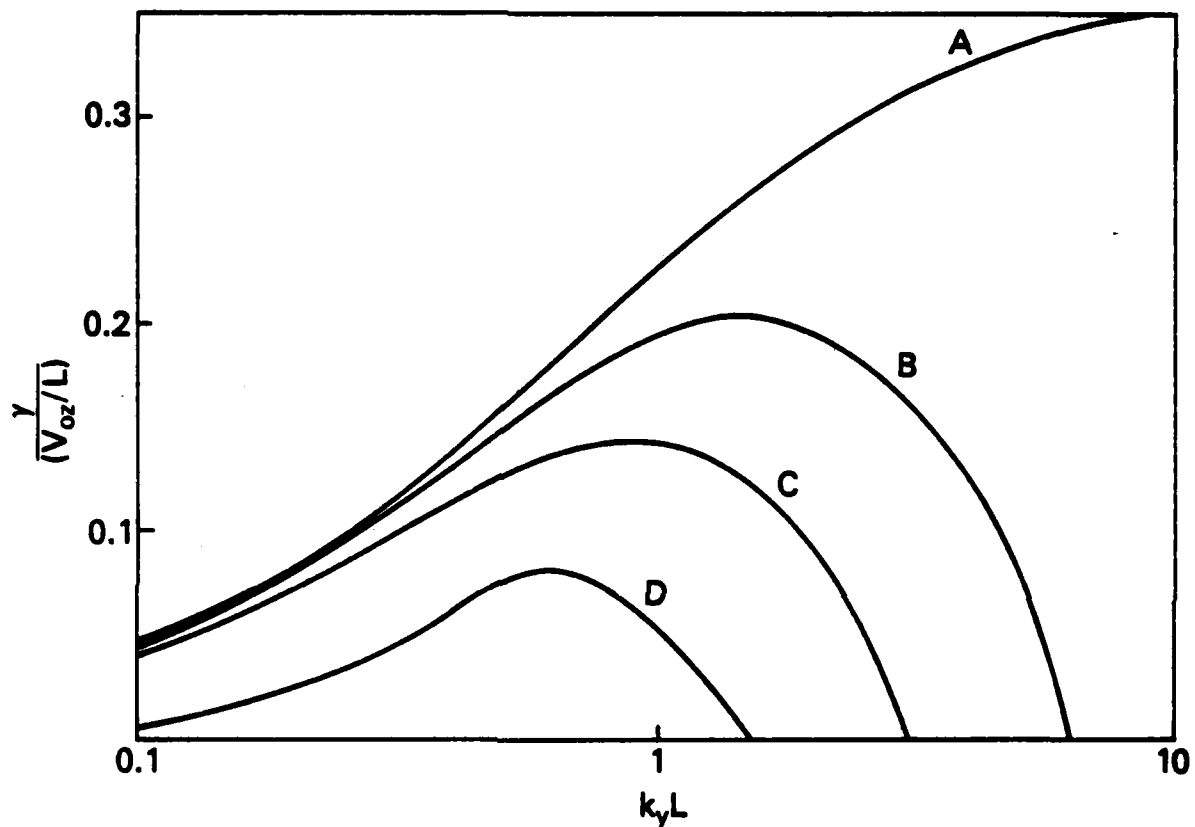


Figure 3. Generalized current convective instability as a function of $\hat{s} (\equiv \bar{V}_{oy}/V_{oz})$. Curve A refers to $\hat{s} = 0$. Curves B, C, and D refer to $s = 0.5, 1$, and 2 , respectively. We used $\delta = 0.8$, $v_{ei}/\Omega_e = 10^{-4}$, and $v_{in}/\Omega_i = 10^{-4}$.

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